Numerical Investigation of Nonlinear Internal Wave Generation and Breaking in Straits

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Award Number: N000140910832

LONG-TERM GOALS

Our long-term goals are to develop a physical understanding of the processes which lead to mixing in the ocean, with the aim of using this understanding to develop parameterizations of mixing suitable for global and regional models, and applying such models to societally relevant problems. A particular focus is the mixing induced by tidal flow over topography, and mixing induced by breaking nonlinear internal waves.

OBJECTIVES

The scientific objectives of this study are to explore internal waves generated by tidal flow through straits in the region close to the sill. Our geographic focus is the Luzon Straits. A particular scientific focus is nonlinear overturning and breaking within the straits leading to mixing and modification of the wave field. One possibility which we examine is whether transient internal hydraulic jumps are possible in the Luzon Straits, whether these jumps are released to propagate toward the topography as internal bores when the flow relaxes, and whether the bores lead to local mixing. We explore the details of the Luzon Strait topography to identify locations particularly conducive to local overturning processes. The Luzon Strait features two parallel north south oriented ridges; we examine how the wave fields of the two ridges interact and affect wave generation and mixing processes. We also examine the importance of three-dimensional bathymetry in determining the locations of mixing. To summarize, our goals are to (a) examine the dependence of nonlinear features and local breaking at the generation site on topographic shape and stratification; (b) evaluate how the interaction between the ridges affect the mixing; (c) examine the extent to which the mixing processes are determined by three-dimensional topography variations.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2013**	2. REPORT TYPE	3. DATES COVERED **00-00-2013 to 00-00-2013**

4. TITLE AND SUBTITLE **Numerical Investigation of Nonlinear Internal Wave Generation and Breaking in Straits**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Princeton University,Atmosphere and Ocean Sciences Program,300 Forrestal Drive,Princeton,NJ,08544**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**6**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

APPROACH

We employ the nonhydrostatic MITgcm in both 2- and 3-dimensions to carry out simulations of increasing complexity, focusing the resolution on the regions close to the sill where overturning is most likely to occur. The MITgcm is well-suited for this study, having been used for numerous studies of nonlinear internal tides (e.g. Legg and Klymak, 2008). MITgcm is a *z*-coordinate model and it applies a simple vertical dissipation and mixing scheme that computes vertical viscosities and diffusivities computed by Thorpe sorting unstable density profiles (Klymak and Legg, 2010). Typical resolutions near the sill are O(100m) in the horizontal and O(10m) in the vertical. Most calculations have been performed on the NAVY cluster Da Vinci.

Recently, we have performed high-resolution three-dimensional 10-day simulations of the double ridge coinciding with the timing of the 2011 IWISE field program. The model set-up has a high horizontal resolution of 250 m and a vertical resolution of 15 m (992 x 1120 x 154 grid cells). The high horizontal resolution is concentrated in areas where the observationalists have the majority of their moorings. The model uses realistic topography merged from high-resolution gridded multibeam data with a resolution of ∼300 m and SRTM30 PLUS data from the Smith and Sandwell data base with a resolution of ∼1 km. The density stratification is derived from temperature and salinity data collected in between the ridges. In the model, the density is only a linear function of temperature. The tidal forcing at the east, west, north, and south model boundaries zonal and meridional barotropic velocities constructed from amplitudes and of eight tidal frequencies. The amplitudes and phases are extracted from the TPXO7.2 tidal inversion at the location of the model boundaries. The interior velocity fields are quadratically nudged to the barotropic tidal velocities over 15 cells in from the boundaries. The interior temperature is nudged to a time-invariant temperature profile at the boundaries.

WORK COMPLETED

Funding was awarded in spring of 2009, but Maarten Buijsman only joined the project in September 2010. In the first year we completed a 2D study of the impact of topographic shape on the nonlinear waves, breaking and dissipation in the straits, comparing results with observations from the 2010 Luzon Straits pilot study. 3D calculations for the purposes of guiding the observations in 2011 summer were also carried out. In the second year, the first year's work was documented and published (Buijsman et al 2012, Klymak et al 2012a, Klymak et al 2012b, Pinkel et al 2012), and regional low and high resolution 3D model runs were performed to examine the effect of 3D topography on the nonlinear waves and dissipation.

In the third year of this subproject, the results of the 3D studies have been written up and submitted to the Journal of Physical Oceanography (Three Dimensional Double Ridge Internal Tide Resonance in Luzon Strait by M.C Buijsman and 9 co-authors) and is currently in review. Additionally, 3D high resolution simulations of the double ridge have been finished and their results analyzed. Currently they are being summarized in a journal article (The nonlinear energy balance in Luzon Strait by M.C. Buijsman, S. Legg and J. Klymak). These 3D high resolution simulations are discussed below.

RESULTS

High Resolution 3D Simulations

The High Resolution 3D Simulations are utilized to better understand the importance of nonlinear effects in Luzon Strait. Therefore, we analyze the full, time-mean, depth-integrated, baroclinic energy balance equation. It reads:

$$\left\langle \frac{\partial \boldsymbol{E}}{\partial t} + \nabla \cdot \mathbf{F}_p + \nabla \cdot \mathbf{u}E + M + D = C + A_{h0} \right\rangle$$

where, from left to right, we have the tendency of kinetic and available potential energy, the divergence of the linear pressure flux, the divergence of the nonlinear advective flux, the small and ignored diapycnal mixing and horizontal diffusion term, and the nonlinear dissipation on the left-hand side, and the linear conversion and nonlinear conversion on the right-hand side. The brackets refer to time averaging. The tendency term becomes small after time averaging and is not discussed here. While in most internal tide studies only the linear pressure flux divergence and linear conversion are considered, we demonstrate that in Luzon Strait the nonlinear terms (shown in red) cannot be neglected.

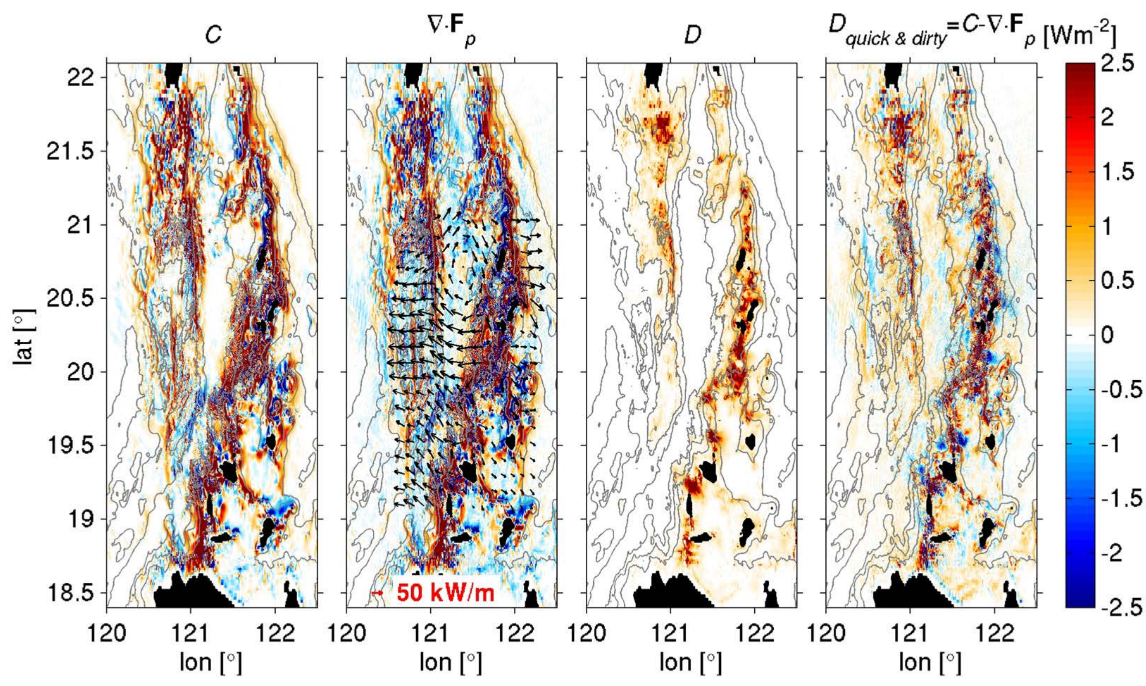

Figure 1. The energy terms, from left to right, are the linear conversion, the pressure flux divergence, the dissipation computed by the model, and the dissipation estimated from the difference between conversion and pressure flux divergence (referred to as quick and dirty dissipation). The vectors in the second panel are the linear pressure fluxes plotted only where the horizontal grid size is 250 m.

In most internal tide studies, the energy balance is considered between linear conversion on the one hand and pressure flux divergence and dissipation on the other. Often dissipation is not directly computed, but instead is diagnosed from the difference between conversion and pressure flux divergence (referred to as diagnosed dissipation). It is shown in Figure 1 that in Luzon Strait the dissipation reported by the model is not the same as the diagnosed dissipation. For example, areas near the steep ridges have negative dissipation rates that can be considered unrealistic and there is a relatively large dissipation in the 3.5 km deep trench between the ridges. These areas with negative dissipation coincide with the occurrence of large nonlinear lee waves.

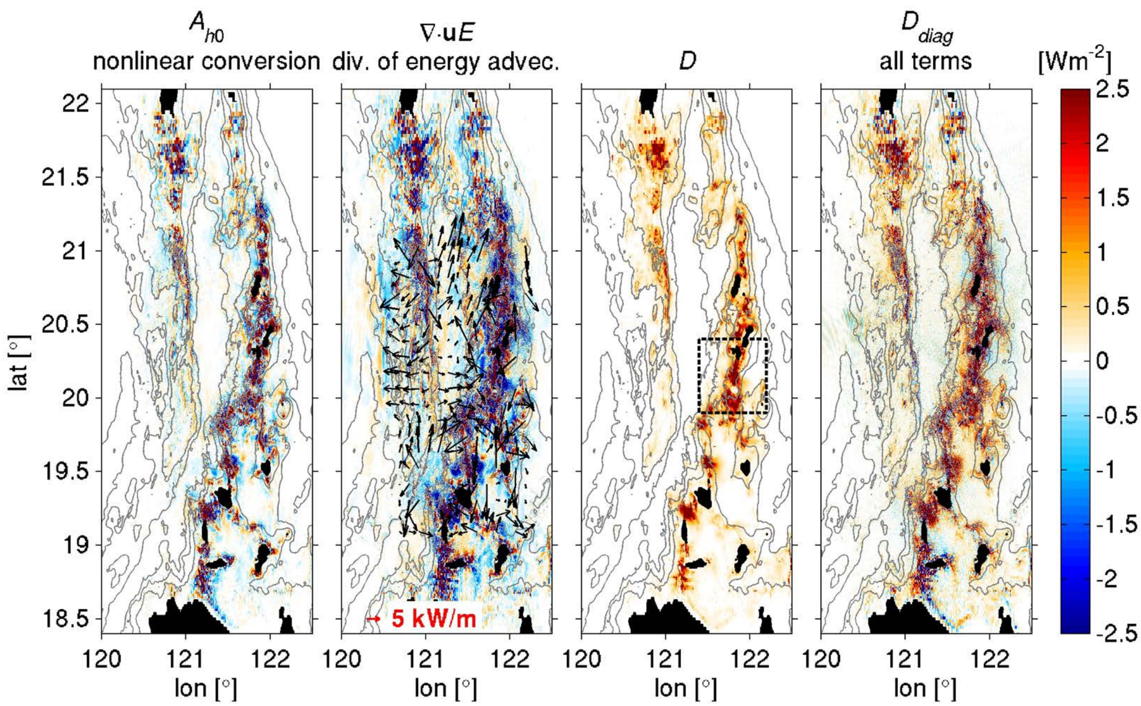

Figure 2. The energy terms, from left to right, are the nonlinear conversion, the advective flux divergence, the dissipation computed by the model, and the dissipation estimated from all terms in the energy balance except the reported dissipation (referred to as diagnosed dissipation). The vectors in the second panel are the nonlinear advective fluxes plotted only where the horizontal grid size is 250 m and where the fluxes are smaller than 5 kW/m.

Albeit smaller than the linear terms in Figure 1, the nonlinear terms in Figure 2 are large near the ridge crests. The advective flux divergence is positive near the ridges in the second panel in Figure 2. This implies that the advective fluxes originate here. They can be as large as 80 kW/m. Several kilometers away from the ridge crests the advected energy is deposited. Hence the advective flux divergence is negative here. When the diagnosed dissipation is computed using all the terms in the energy balance equation, except the reported dissipation, the areas of negative dissipation disappear (fourth panel in Figure 2). The nonlinear conversion and advective flux divergence are therefore essential in closing the energy balance.

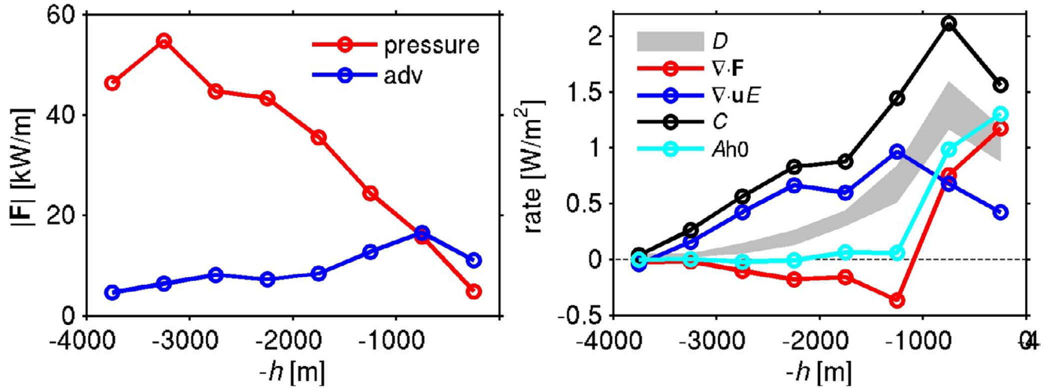

Figure 3. Left panel: The absolute pressure and advective fluxes averaged in 500 m depth bins. Right panel: the most important energy terms averaged in 500 m depth bins. The grey area is lower bounded by the reported dissipation and upper bounded by the diagnosed dissipation using all nonlinear energy terms.

The linear pressure fluxes terms are still much larger than the advective fluxes in deep water (left panel of Figure 3). The advective fluxes are about 10% of the pressure fluxes in water deeper than 3000 m. Hence, the large-scale wave patterns in Luzon Strait, as represented by the pressure fluxes can still be considered linear. In contrast, the linear fluxes and energy terms are of similar magnitude as the nonlinear ones in shallow water near the ridge crests (both panels in Figure 3), where the turbulent lee waves occur. The linear conversion is still the largest in all depth bins. However, the nonlinear conversion, advective flux divergence, and dissipation are larger than the linear flux divergence in most water depths.

The strong nonlinearities coincide with the occurrence of breaking lee waves. These waves cause Luzon Strait to be a highly dissipative region. The fraction of energy converted from the barotropic tide lost to dissipation is about 45% when integrated over several tidal cycles. This is almost double the fraction observed in high-resolution 2D simulations (Buijsman et al., 2012) but of similar magnitude as in other 3D simulations by Jan et al (2008) and Alford et al. (2011).

IMPACT/APPLICATIONS

These simulations have provided important information on the 3-D flow and turbulence in the Luzon Strait system, information which is contributing to general understanding of internal waves on complex geometry, and aiding in the interpretation of observations in this specific region. Four papers have been published so far: Buijsman et al (2012), Klymak et al (2012), Pinkel et al (2012), and Klymak et al (2013). One manuscript is in review (Buijsman et al, 2013) and one manuscript describing these new 3D simulations is in preparation. This work has been presented at the Warnemunde Turbulence Days 2011 and Ocean Sciences 2012.

RELATED PROJECTS

This work is a component of the Internal Waves in Straits Experiment. We are working closely with other IWISE researchers, particularly Jody Klymak, Rob Pinkel and Matthew Alford. The work is also related to an NSF/NOAA-funded climate process team on internal-wave driven mixing (PI Jen MacKinnon), with which Legg is collaborating.

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